GEOMORPHIC EFFECTS OF LARGE DEBRIS FLOWS ON CHANNEL MORPHOLOGY AT NORTH FORK MOUNTAIN, EASTERN WEST VIRGINIA, USA

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ABSTRACT

Extreme rainfall in June 1949 and November 1985 triggered numerous large debris flows on the steep slopes of North Fork Mountain, eastern West Virginia. Detailed mapping at four sites and field observations of several others indicate that the debris flows began in steep hillslope hollows, propagated downslope through the channel system, eroded channel sediment, produced complex distributions of deposits in lower gradient channels, and delivered sediment to floodwaters beyond the debris-flow termini. Based on the distribution of deposits and eroded surfaces, up to four zones were identified with each debris flow: an upper failure zone, a middle transport/erosion zone, a lower deposition zone, and a sediment-laden floodwater zone immediately downstream from the debris-flow terminus. Geomorphic effects of the debris flows in these zones are spatially variable. The initiation of debris flows in the failure zones and passage through the transport/erosion zones are characterized by degradation; 2300 to 17 000 m^3 of sediment was eroded from these zones. The total volume of channel erosion in the transport/erosion zones was 1·3 to 1·5 times greater than the total volume of sediment that initially failed, indicating that the debris flows were effective erosive agents as they travelled through the transport/erosion zones. The overall response in the deposition zones was aggradation. However, up to 43 per cent of the sediment delivered to these zones was eroded by floodwaters from joining tributaries immediately after debris-flow deposition. This sediment was incorporated into floodwaters downstream from the debris-flow termini causing considerable erosion and deposition in these channels. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

Debris flows in mountainous regions are capable of transporting large quantities of sediment downslope, producing complex distributions of deposits and eroded surfaces throughout their flow tracks, and dramatically modifying channel morphology (Hack and Goodlett, 1960; Scott, 1971; Williams and Guy, 1973; Campbell, 1975; Bogucki, 1976; Pierson, 1980, 1986; Benda, 1990; Wohl and Pearthree, 1991). Despite the recognized importance of debris flows on channel morphology, little attention has been given to the spatial distribution of deposits and eroded surfaces associated with debris flows. Most mapping of debris flows has concentrated on debris fans (Hooke, 1967; Wells and Harvey, 1987; Whipple and Dunne, 1992) and has not focused on deposits and eroded surfaces in upper reaches impacted by debris flows. Although debris flows have been recognized as important geomorphic agents in removing sediment from steep mountainous channels, only a few studies have quantified the volume of sediment eroded by debris flows during transport and the contribution of this eroded sediment to the overall volume of erosion (Caine, 1976; Dietrich and Dunne, 1978; Benda, 1990). Knowledge of the volume of sediment eroded and deposited during all phases of a single debris flow is important to determining the geomorphic effects that debris flows have on mountainous terrain.

North Fork Mountain in eastern West Virginia is an excellent setting for addressing these concerns because the area has experienced two extreme storms that initiated numerous large debris flows on its steep slopes in the

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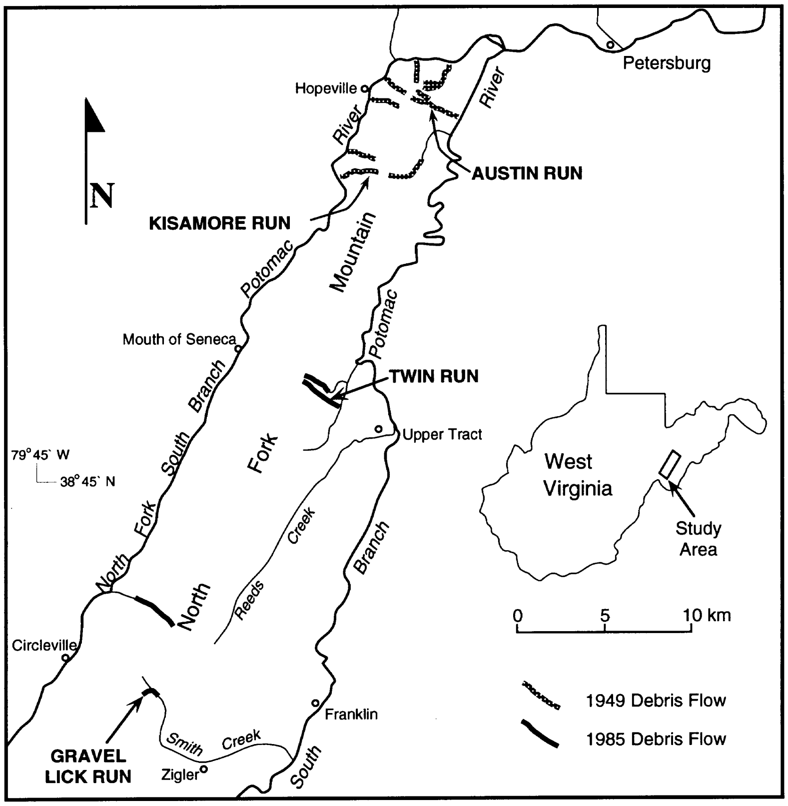


Figure 1. Location map of the study area. Shown are the locations of some of the large debris flows that occurred on North Fork Mountain. Names of the four large debris-flow channels studied in detail are given in bold type

past 45 years (Figure 1). Although the occurrence of these debris flows has been documented by other researchers in the North Fork Mountain area (Stringfield and Smith, 1956; Felton, 1978; Jacobson *et al*., 1987, 1993; Kite *et al*., 1987), the studies did not examine the erosional and depositional characteristics of the debris flows and their effects on channel morphology. In this paper, we describe and delineate the spatial distribution of deposits and eroded surfaces associated with four debris flows, quantify the distribution and volume of sediment eroded and deposited along the course of each debris flow, and document the occurrence of older debris-flow deposits.

The large mass movements that occurred on North Fork Mountain typically began as debris slides, but quickly transformed into debris flows when the failed mass entered steep, first-order channels. These complex mass movements are best classified as debris slides/debris flows (Varnes, 1978), but we refer to them as debris flows in this paper for brevity and because this process was dominant along the flow track. The terms debris avalanche (Jacobson *et al*., 1987) and debris slide/avalanche flow (Jacobson *et al*., 1993) have been used to describe the large 1985 mass movements on North Fork Mountain. A debris avalanche is a very rapid to extremely rapid debris flow (Varnes, 1978) that locally loses contact with the underlying surface, leaving a relatively undisturbed 'skim zone' (Orme, 1987). Skim zones were not observed along the 1949 and 1985 flow tracks in this study, indicating that debris flow is a more appropriate term to describe the mass movements on North Fork Mountain.

PHYSICAL SETTING

North Fork Mountain, West Virginia, is situated in the headwaters of the Potomac River (Figure 1), located within the Valley and Ridge Physiographic Province, and underlain by deformed Palaeozoic sedimentary rocks.

This prominent ridge has an elevation ranging between 1000 and 1250 m and is approximately 700 m higher than the major valley floors. The crest of North Fork Mountain is capped by a resistant orthoquartzite and its lower slopes are underlain by less resistant shales, limestones and argillaceous sandstones.

Four debris flows on North Fork Mountain were selected for detailed study: Austin Run and Kisamore Run from the 1949 storm and Twin Run and Gravel Lick Run from the 1985 storm (Figure 1). The drainage basins of the four debris flows have areas ranging from 0·96 to 4·53 km^2, reliefs ranging from 350 to 600 m, elongated shapes and ephemeral channels. These basins are forested, although small pastures occur locally on footslopes. Aerial photographs indicate that the debris flows removed almost all of the vegetation along their courses. At the time of this field study, 1993, most areas impacted by the 1949 debris flows were revegetated by trees, shrubs and grasses. Only minimal revegetation had occurred in areas impacted by the 1985 debris flows.

THE 1949 AND 1985 STORMS

On 17 and 18 June 1949, an intense convectional storm produced over 400 mm of rainfall in a 24-hour period in the North Fork Mountain area (Stringfield and Smith, 1956; Miller, 1987). This storm was twice as large as the 100-year recurrence estimates for a 24-hour rainfall in the region (Hershfield, 1961). The 1949 storm resulted in record-breaking floods on the South Branch Potomac and the North Fork South Branch Potomac Rivers and triggered numerous debris flows in soils derived from sandstone on the steep, upper slopes of North Fork Mountain (Stringfield and Smith, 1956; Figure 1).

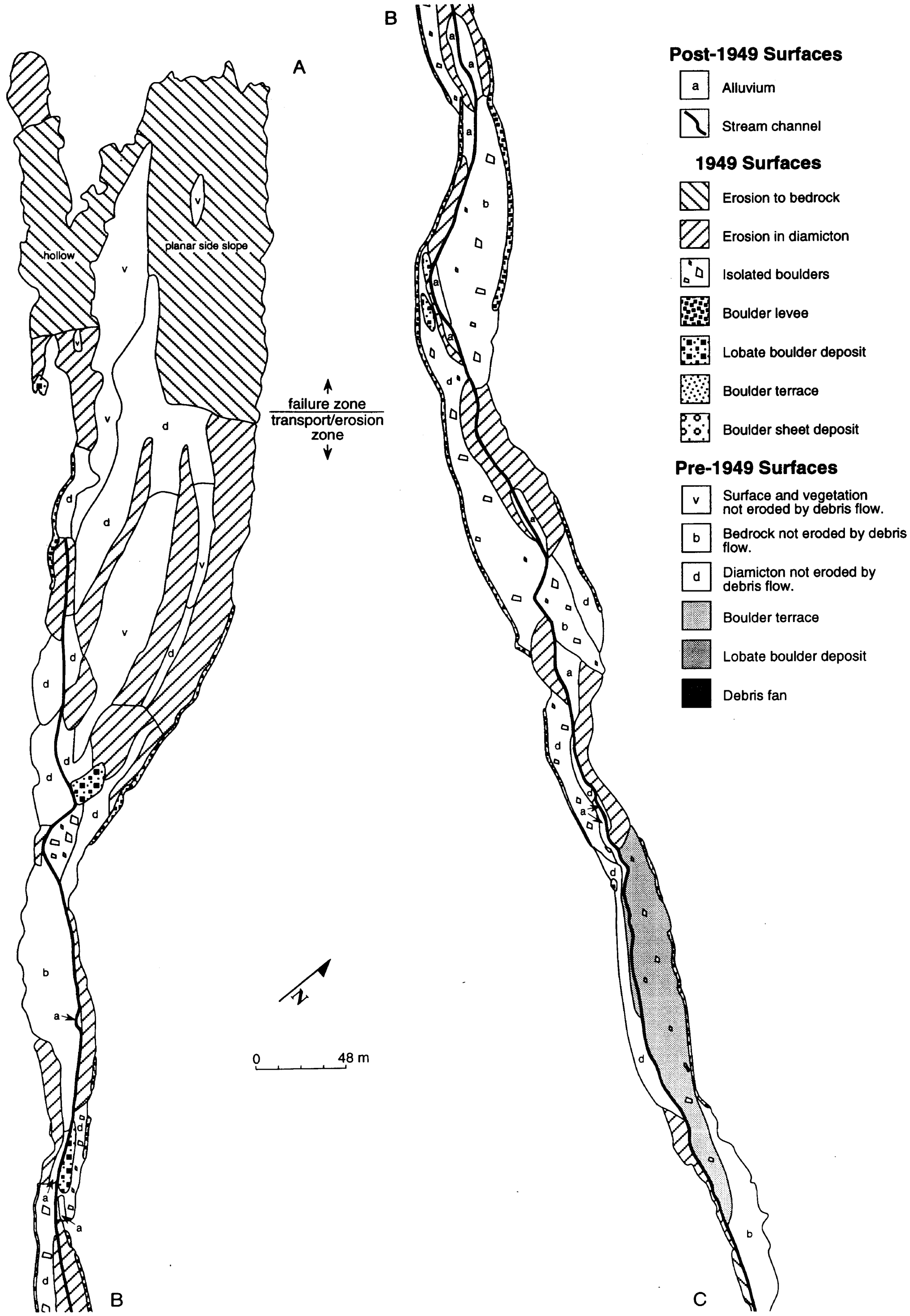
On 3–5 November 1985, remnants of Hurricane Juan combined with several low-pressure cells on the eastern coast of the United States to form a single, low-pressure system that generated over 200 mm of rainfall in a 48-hour period in West Virginia and Virginia (Miller, 1987; Clark *et al*., 1987; Colucci *et al*., 1993). This storm had an estimated recurrence interval of 80 to 300 years (Colucci *et al*., 1993). The 1985 storm produced a record-breaking flood on the South Branch Potomac River and triggered several large debris flows in soils derived from sandstone on the upper slopes of North Fork Mountain (Figure 1), as well as hundreds of small landslides in soils derived from shales or limestones on the lower slopes of the mountain (Clark *et al*., 1987; Jacobson *et al*., 1987, 1993; Miller, 1987). The most intense precipitation, in excess of 250 mm in 48 hours (Colucci *et al*., 1993), was in close proximity to where the largest debris flows occurred on North Fork Mountain.

METHODOLOGY

Four debris flows were selected to study their erosional and depositional behaviour. Field work, a critical component of this research, included: (1) mapping erosional and depositional features associated with debris flows; (2) measuring the volume of sediment eroded by debris flows; and (3) determining the volume of sediment deposited by the debris flows. Geomorphic and sedimentologic features were mapped onto enlarged air photos (1:1200 to 1:1500 scale) taken within three years of each debris flow. Seventeen mapping units were used to describe erosional and depositional morphology, deposit texture and relative age of deposits (Figures 2–5). Erosional volumes were calculated by reconstructing the mean cross-sectional areas of 125 eroded surfaces and measuring their lengths. The pre-erosion surface was reconstructed by projecting the surface profile of the adjacent uneroded slope over the eroded surface. The volume of debris-flow deposits was calculated from area measurements and thickness estimates of each mapped deposit.

CHARACTERISTICS OF THE 1949 AND 1985 DEBRIS FLOWS

Up to four zones can be delineated in each debris flow: an upper failure zone, a middle transport/erosion zone, a lower deposition zone, and a sediment-laden floodwater zone immediately downstream from the debris-flow terminus. The first three zones listed are similar to those used by Bogucki (1976), Pierson (1985), VanDine (1985), and Cenderelli and Kite (1993). The failure zone is an area in which failure of unconsolidated sediment or bedrock is initiated, generating the debris flow. The transport/erosion zone consists primarily of erosional features produced by the debris flow as it travelled through the channel system. The deposition zone is an area in


A
B
C
hollow
planar side slope
failure zone
transport/erosion zone
0
48 m
N
Post-1949 Surfaces
Alluvium
Stream channel
1949 Surfaces
Erosion to bedrock
Erosion in diamicton
Isolated boulders
Boulder levee
Lobate boulder deposit
Boulder terrace
Boulder sheet deposit
Pre-1949 Surfaces
Surface and vegetation not eroded by debris flow.
Bedrock not eroded by debris flow.
Diamicton not eroded by debris flow.
Boulder terrace
Lobate boulder deposit
Debris fan

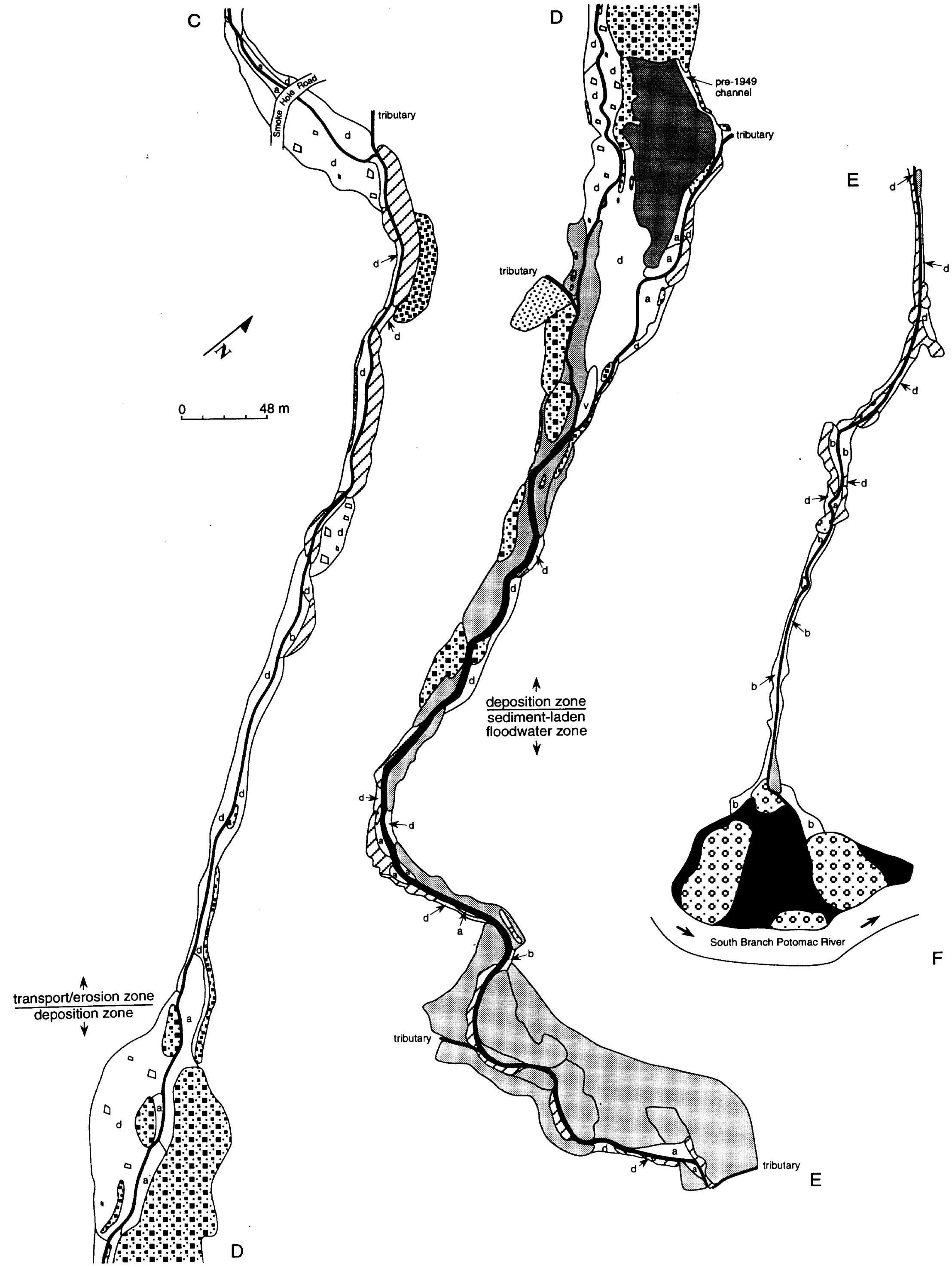
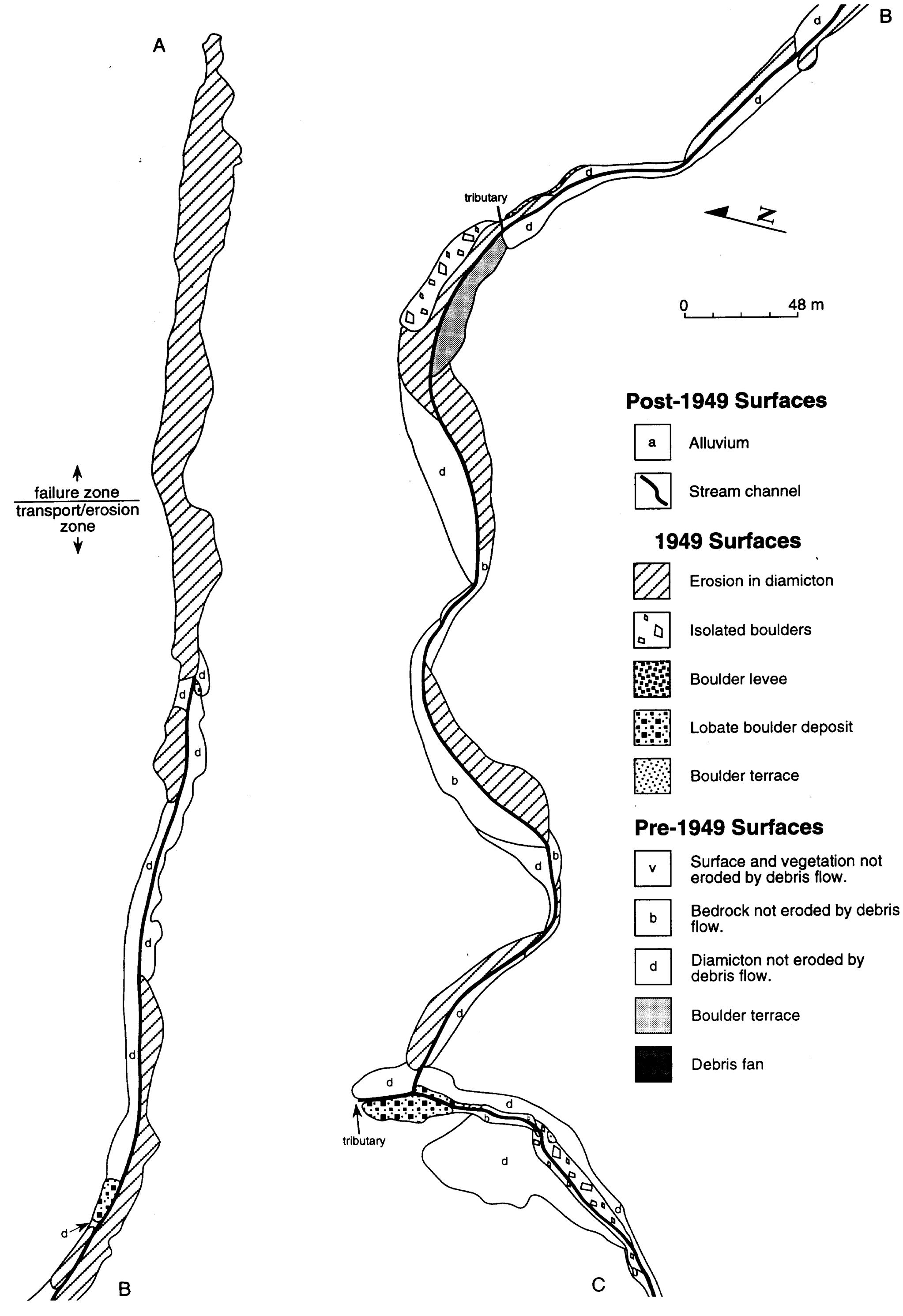


Figure 2. Geomorphic map of erosional and depositional features associated with the 1949 debris flow on Austin Run (modified from Cenderelli, 1994)



A
failure zone
transport/erosion zone
B
tributary
N
0 48 m
C
Post-1949 Surfaces
Alluvium
Stream channel
1949 Surfaces
Erosion in diamicton
Isolated boulders
Boulder levee
Lobate boulder deposit
Boulder terrace
Pre-1949 Surfaces
Surface and vegetation not eroded by debris flow.
Bedrock not eroded by debris flow.
Diamicton not eroded by debris flow.
Boulder terrace
Debris fan

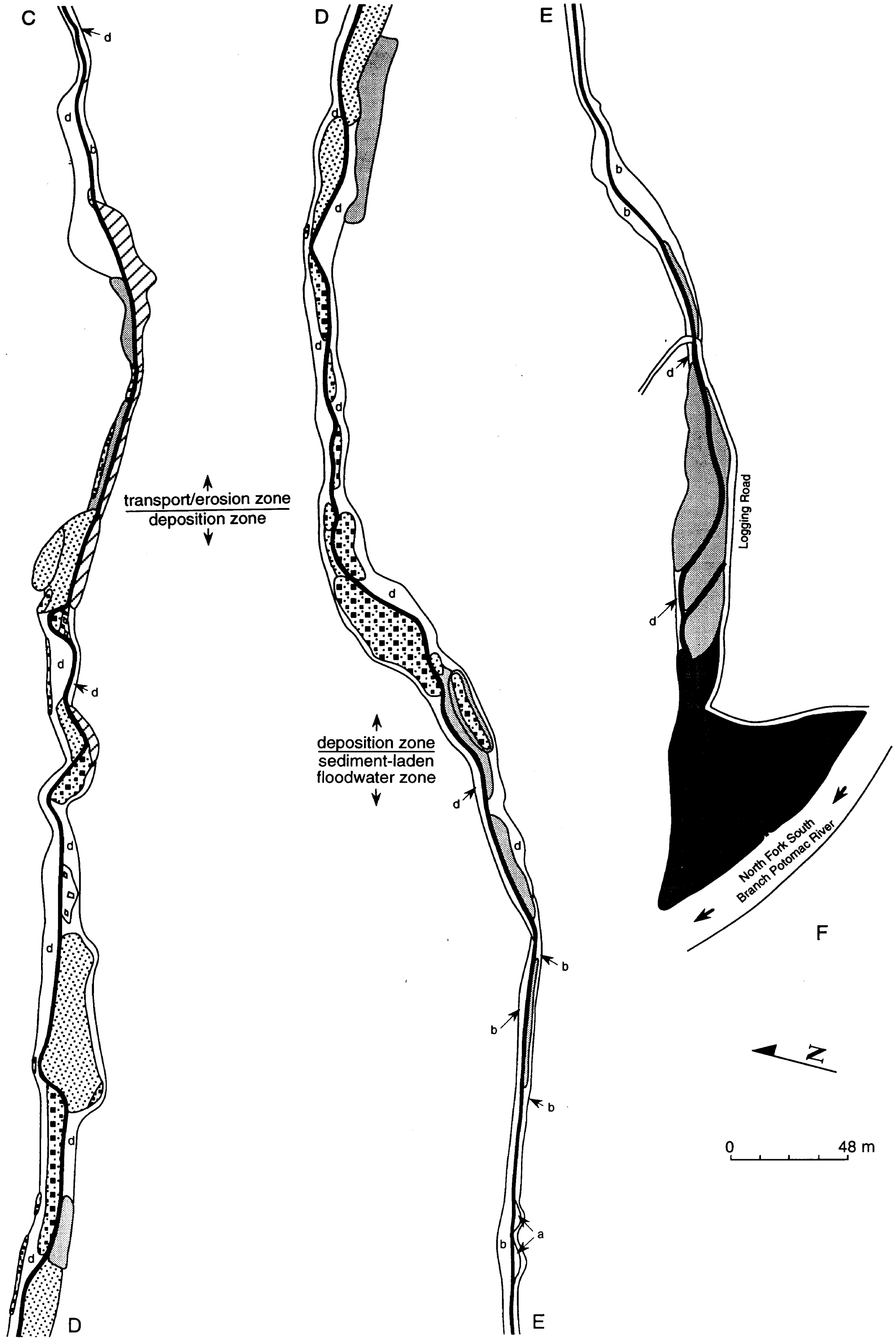
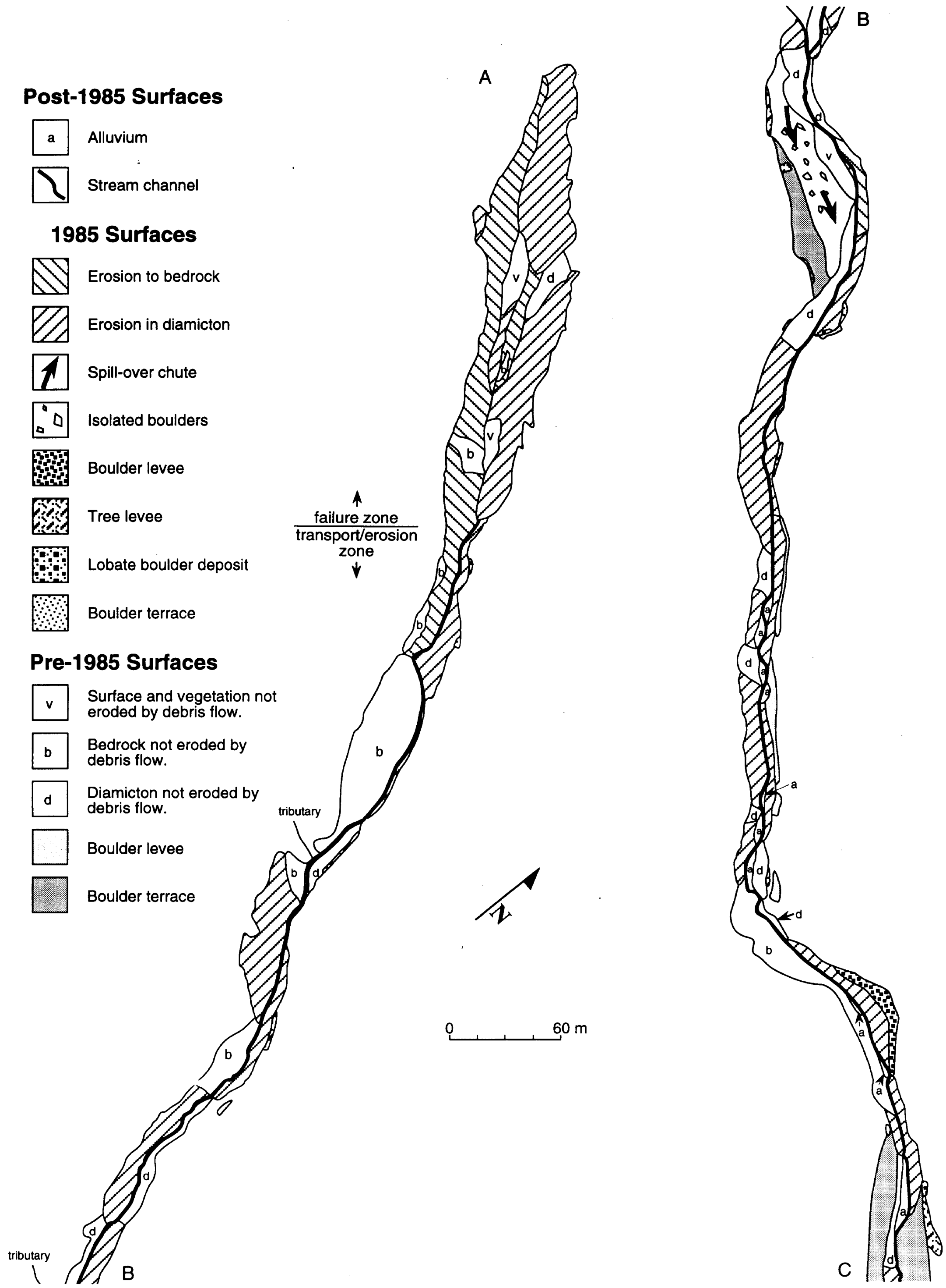


Figure 3. Geomorphic map of erosional and depositional features associated with the 1949 debris flow on Kisamore Run (modified from Cenderelli, 1994)



Post-1985 Surfaces
a Alluvium
Stream channel
1985 Surfaces
Erosion to bedrock
Erosion in diamicton
Spill-over chute
Isolated boulders
Boulder levee
Tree levee
Lobate boulder deposit
Boulder terrace
Pre-1985 Surfaces
v Surface and vegetation not eroded by debris flow.
b Bedrock not eroded by debris flow.
d Diamicton not eroded by debris flow.
Boulder levee
Boulder terrace
A
B
C
failure zone
transport/erosion zone
tributary
tributary
N
0
60 m

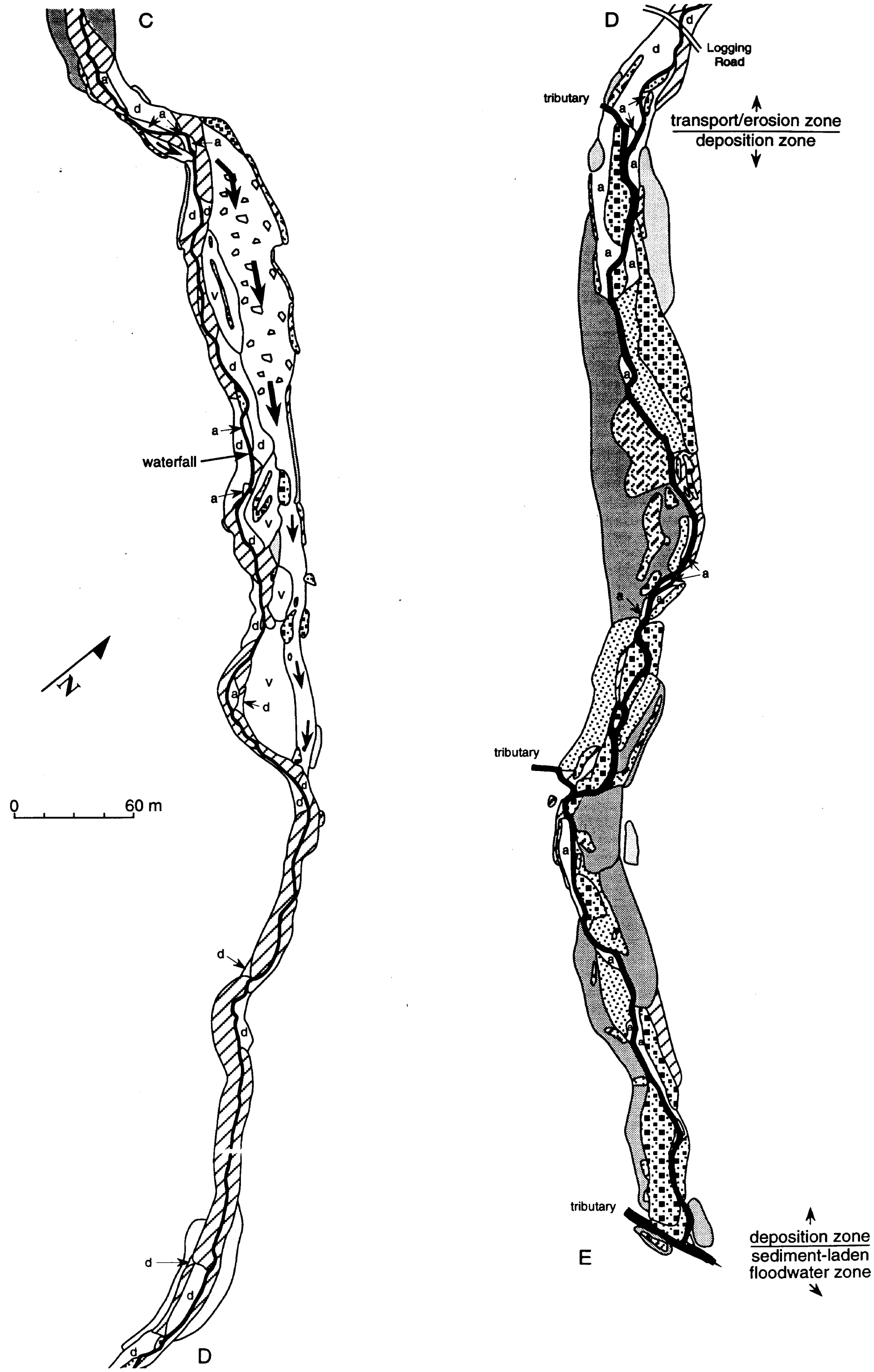


Figure 4. Geomorphic map of erosional and depositional features associated with the 1985 debris flow on Twin Run (modified from Cenderelli, 1994)

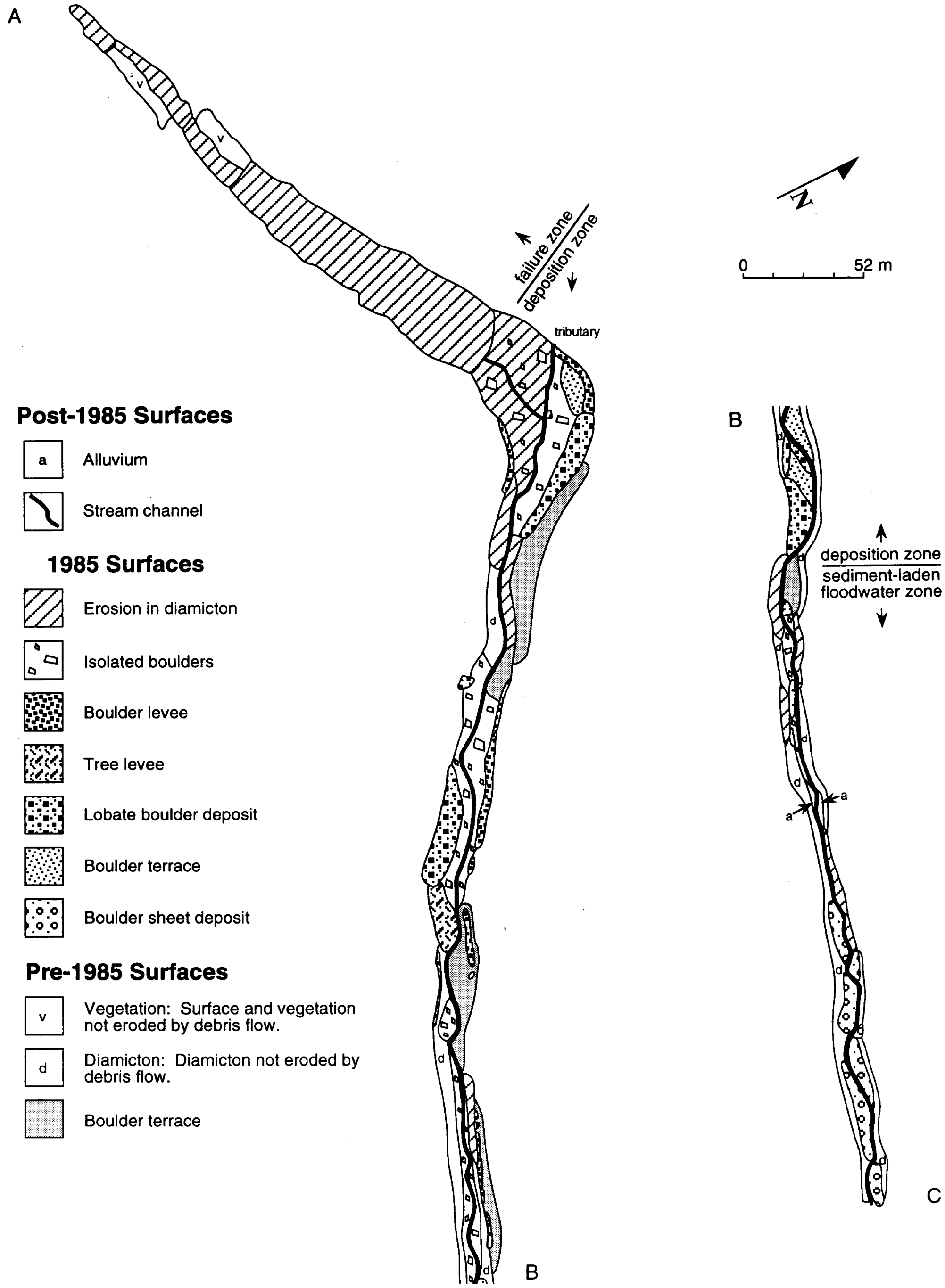


Figure 5. Geomorphic map of erosional and depositional features associated with the 1985 debris flow on Gravel Lick Run (modified from Cenderelli, 1994)

Table I. Summary of selected basin morphometry variables of the failure, transport, deposition, and sediment-laden (SL) floodwater zones of each debris flow. Not applicable (na) indicates this zone was not identified

Debris flow, date zone	Drainage area (km^2)	Drainage density (km/km^2)	Basin shape	Relief ratio (m/m)	Length (m)	Average gradient (degrees)
Austin Run, 1949						
failure zone	0·035	10·26	3·69	0·41	180	31
transport zone	1·24	2·65	3·05	0·25	1856	11
deposition zone	3·90	2·67	1·88	0·20	564	5
SL floodwater zone	4·53	2·73	2·49	0·18	819	5
Kisamore Run, 1949						
failure zone	0·016	12·40	6·85	0·49	200	28
transport zone	1·28	4·44	2·06	0·28	1400	12
deposition zone	1·73	4·24	3·20	0·23	800	6
SL floodwater zone	1·98	4·01	4·25	0·21	600	5
Twin Run, 1985						
failure zone	0·037	6·42	14·80	0·34	240	28
transport zone	1·23	2·57	4·76	0·23	1960	9
deposition zone	3·82	2·71	2·24	0·21	648	5
SL floodwater zone	12·39	2·31	2·15	0·13	1440	3
Gravel Lick Run, 1985						
failure zone	0·041	5·62	10·33	0·35	230	31
transport zone	na	na	na	na	na	na
deposition zone	0·78	4·36	2·59	0·25	500	10
SL floodwater zone	0·96	4·10	2·56	0·23	270	8

Figure 6. Photograph of the Twin Run failure zone. Failure zones are marked by distinct vertical scarps along the failure margin. Note that the depth of failure is greatest where bedrock is exposed

which most of the debris flow deposited its sediment and organic material. The sediment-laden floodwater zone is characterized by thin sheet deposits and erosion of the channel floor. Some important basin morphometry variables for these zones are summarized in Table I.

Failure zone

Failure zones are steep and situated in unchannelized hollows, planar side slopes, or a combination of both. Distinct scarps, up to 2·5 m high, along the upper and lateral margins of the failure zones, distinguish failure surfaces from adjacent undisturbed slopes (Figure 6). Undisturbed sediment exposed in the scarps indicates that the failed material consisted primarily of a clast-supported sandy, bouldery diamicton derived from orthoquartzite. The failed material also included trees and shrubs growing on the surface of the pre-failure sediment.

The slope aspect, structure and lithology of underlying bedrock, and the physical characteristics of the failure surface for each failure zone vary among the debris flows (Table II, Figures 2–5). The depth of failure

Table II. Physical characteristics of the debris-flow failure zones

Debris flow, date	Head scar dimensions width (m)	length (m)	area (km^2)	gradient (degrees)	Sediment that initially failed	Failure plane surface	Underlying bedrock orientation	Slope aspect
Austin Run, 1949	102	180	0·014	31	sandy, bouldery diamiction	90% bedrock, orthoquartzite; 10% daimicton derived from orthoquartzite	strike 25° dip 30° SE	southeast, 115°; parallel to bedrock dip
Kisamore Run, 1949	24	200	0·0027	28	sandy, bouldery diamicton	100% diamicton derived from arg. sandstone	strike 30° dip 15° SE	west, 275°; opposite to bedrock dip
Twin Run, 1985	59	240	0·0086	28	sandy, bouldery diamicton	50% bedrock, orthoquartzite; 50% diamicton derived from orthoquartzite	strike 12° dip 30° SE	southeast, 145°; oblique to bedrock dip
Gravel Lick Run, 1985	32	230	0·0039	31	sandy, bouldery diamicton	100% diamicton derived from arg. sandstone	strike 40° dip 15° SE	northeast, 60°; perpendicular to bedrock dip

Figure 7. Photograph of the Twin Run transport/erosion zone. Transport/erosion zones are characterized by scoured channel side slopes and channel floors. Note the tree and shrub roots exposed and overhanging the eroded side slope

was shallower in the diamicton surfaces (Kisamore Run and Gravel Lick Run) than in the bedrock surfaces (Austin Run and Twin Run; Table II). Striations present on the sandstone bedrock failure surfaces of Austin Run and Twin Run indicate that the initial mechanism of failure in these debris flows was probably sliding (Kite *et al*., 1987).

Transport/erosion zone

The debris flows that began in the failure zones of Austin Run, Kisamore Run and Twin Run propagated downslope through the pre-existing channel systems. The transport/erosion zones have lengths of between 1400 and 1960 m, average gradients between 9° and 12°, and include first-, second- or third-order channels (Table I). A distinguishable transport/erosion zone did not develop on Gravel Lick Run because of abrupt changes in gradient (22°) and flow direction (90°) between the failure zone and a third-order channel it intersected (Figure 5). The sudden decrease in gradient and the sharp channel bend reduced the momentum of the debris flow, inhibited further transport, and caused deposition.

Transport/erosion zones are characterized by scoured channel side slopes and floors (Figure 7). Debris-flow erosion exposed fresh outcrops of bedrock or diamicton (Figures 2–4). Typically, the surface immediately above the eroded slope is undercut, exposing tree and shrub roots (Figure 7). Eroded surfaces have lengths of 10 to 200 m, heights of 3 to 11 m, and erosion depths up to 2 m. The debris flows removed most of the vegetation within the transport/erosion zones and scarred trees along the outer margins of the flow. Spill-over chutes, formed when part of the debris-flow mass flowed out of the pre-existing channel and re-entered the channel further downstream, were identified on Twin Run (Figure 4). A few sheared root masses on the spill-over chute surface suggest that the depth of erosion was less than 0·3 m.

Figure 8. Photograph of a clast-supported lobate boulder deposit in the Twin Run deposition zone

Minor deposits are present in the transport/erosion zones, primarily discontinuous boulder and tree levees (Figures 2–4). Boulder levees are composed primarily of clast-supported cobbles and boulders with minor amounts of sand, pebbles and woody debris. Well-developed paired and unpaired boulder levees occur along the margins of the transport/erosion zone on Austin Run (Figure 2), but not on Kisamore Run and Twin Run (Figures 3 and 4). Boulder levees on Austin Run were best developed where the valley widened, the side slopes were moderately to gently sloped, and channel entrenchment was minimal. In contrast, the transport/erosion zones of Kisamore Run and Twin Run have predominantly narrow valleys, steep side slopes, and deeply entrenched channels that inhibited the formation of extensive boulder levees. Tree levees, consisting mostly of tree trunks and limbs, occur along the margins in the transport/erosion zone of Twin Run, a 1985 debris flow (Figure 4), but not in Austin Run and Kisamore Run, which are 1949 debris flows. Trees are beginning to rot in the levees on Twin Run (less than eight years after the debris flow occurred), suggesting that these deposits in this humid climate survive only for a short time after deposition. This rapid decay of organic material prevented the tree levees from being preserved in the older Austin Run and Kisamore Run transport/erosion zones.

Deposition zone

Deposition zones are characterized by multiple lobate boulder deposits, boulder terraces, boulder levees, tree levees and isolated boulders (Figures 2–5). Deposition zones have lengths of 500 to 800 m, average gradients of 5° to 10°, and are located in third-order channels (Table I). The doubling to tripling of valley width at the transition from the transport/erosion zone to the deposition zone probably influenced the deposition of the debris-flow mass at Austin Run and Twin Run (Figures 2 and 4), along with a decreasing channel gradient. A decreasing channel gradient and a momentum-reducing sharp channel bend near the end of the transport-erosion zone influenced the location of the deposition zones on Kisamore Run (Figure 3). Erosion of pre-existing deposits by debris flows is minimal in the deposition zones because of the sharp reduction in debris-flow velocity.

Lobate boulder deposits and boulder terraces are the dominant type of debris-flow deposits in the deposition zones (Figures 2–5). The flanks of lobate boulder deposits are detached from valley side slopes, whereas one of the flanks of the boulder terraces is attached to a valley side slope. These deposits have steep fronts and flanks, generally small-scale undulations on their surfaces, lengths of 6 to 138 m, widths of 2 to 48 m, thicknesses of 0·3 to 2·5 m, and areas of 5 to 5220 m^2. Lobate boulder deposits and boulder terraces are poorly to very poorly sorted, clast-supported, not imbricated, massive or inversely graded, and composed primarily of very angular or angular boulders and cobbles, pebbles and sand (Figure 8). Sand and pebbles occupy the interstices between the boulders and cobbles except for the upper 0·3 to 0·5 m of the deposit surfaces. For the most part, the long-axes of cobbles and boulders show no preferred orientation, but small clusters of clasts with weakly developed long-axis orientations perpendicular, parallel or oblique to flow direction occasionally occur in parts of the deposits. The cobbles and boulders are mostly orthoquartzite, the predominant rock type in each source area. The largest clasts are usually concentrated at the surface and downstream ends of each deposit (Figure 8). Clasts do not

Figure 9. Photograph of a scoured channel floor in the Twin Run sediment-laden floodwater zone. View is just downstream of the Twin Run debris-flow terminus

have impact marks, suggesting that flow was laminar (Johnson, 1970; Costa, 1984). Fragile, intact shale clasts within some of the deposits provide additional evidence that flow was laminar or at least that turbulence was greatly suppressed in the flow (Johnson, 1970; Lawson, 1982; Costa, 1984).

The deposition zones of all four debris flows are dissected by channels (Figures 2–5). These post-debris-flow channels probably have different paths than the pre-existing channels buried by the debris-flow deposits, although evidence of this is lacking except on Austin Run, where a segment of a pre-1949 channel was identified approximately 50 m north-northeast of the present-day channel (Figure 2). Hooke (1967), Wohl and Pearthree (1991), Whipple and Dunne (1992) and Cenderelli and Kite (1993) have suggested that the development of channels in debris-flow deposits is the result of hyperconcentrated flow or water flood occurring immediately after debris-flow deposition. Isolated boulders and fluvial deposits in the deposition zones (Figures 2–5) are additional evidence of partial reworking of the debris-flow deposits by floodwaters from joining tributaries immediately after deposition.

Sediment-laden floodwater zone

Channels located immediately downstream from the deposition zones experienced intense erosion and deposition by hyperconcentrated flow or sediment-laden floodwaters (Figure 9). These zones are characterized by thin, clast-suppoorted sheet deposits, undercut side slopes and scoured channel floors (Figures 2, 3 and 5). Sheet deposits are clast-supported, strongly imbricated with the long-axis of most clasts oriented perpendicular to flow direction, and composed primarily of cobbles and small boulders. These physical characteristics suggest that the sheet deposits formed from water-flood processes (Smith, 1986; Wells and Harvey, 1987; Costa, 1988). Sheet deposits on Austin Run and Gravel Lick Run have lengths of 6 to 54 m, widths of 1·5 to 30·0 m, thicknesses of 0·3 to 1·5 m, and areas of 10 to 1440 m^2. Erosion was most extensive on Austin Run and Gravel Lick Run, particularly at valley constrictions where side slopes were undercut (Figures 2 and 5). Eroded valley side slopes on Austin Run and Gravel Lick Run have lengths of 12 to 120 m, heights of 1·5 to 12·0 m and erosion depths up to 2·5 m.

The sediment-laden floodwater zones of Austin Run, Kisamore Run and Gravel Lick Run are located in third-order channels and the Twin Run sediment-laden floodwater zone is situated in the upper segments of a fourth-order channel. Sediment-laden floodwater zones have lengths of 270 to 1440 m and average gradients ranging from 3° to 8° (Table I). Sediment-laden floodwater zones are visible on the earliest post-debris-flow photographs of Austin Run, Kisamore Run and Gravel Lick Run, allowing the mapping of erosional and depositional features (Figures 2, 3 and 5). Although similar features are present in the Twin Run sediment-laden floodwater zone, this zone was shaded by forest canopy on the aerial photographs and was not mapped.

Evidence of past debris-flow activity on North Fork Mountain

The presence of the older debris-flow deposits indicates that debris flows are a recurring geomorphic process in low-order channels on North Fork Mountain. Older debris-flow deposits are located adjacent to and

Table III. Volumes of sediment eroded and deposited for each debris flow

Debris flow, date zone	Length (m)	Volume of sediment eroded (m^3)	Erosion per zone length (m^3/m)	Volume of sediment deposited (m^3)	Deposition per zone length (m^3/m)
Austin Run, 1949					
failure zone	180	7500	41·7	0	0
transport zone	1856	9500	5·2	1600	0·9
deposition zone	564	300	0·5	10 500	18·6
SL floodwater zone	819	3600	4·4	2900	3·5
total	3419	20 900	6·1	15 000	4·4
Kisamore Run, 1949					
failure zone	200	3600	18·0	0	0
transport zone	1400	4600	3·3	500	0·4
deposition zone	800	300	0·4	4400	5·5
total	2400	8500	3·5	4900	2·0
Twin Run, 1985					
failure zone	240	5400	22·5	0	0
transport zone	1960	8200	4·2	700	0·4
deposition zone	648	300	0·5	7400	11·4
total	2848	13 900	4·9	8100	2·8
Gravel Lick Run, 1985					
failure zone	230	2300	10·0	0	0
deposition zone	500	300	0·6	2100	4·2
SL floodwater zone	270	700	2·6	600	2·2
total	1000	3300	3·3	2700	2·7

SL = sediment laden

downstream of the deposition zones (Figures 2–5). In general, older debris-flow surfaces are situated 1 to 3 m above the 1949 and 1985 debris-flow deposits, indicating channel entrenchment prior to the 1949 and 1985 debris flows. Older deposits are differentiated from the 1949 and 1985 debris-flow deposits on the basis of deposit morphology, the presence of lichen-encrusted boulders and 100 to 120-year-old trees on the surface, and soil-profile development. Older debris-flow deposits are subdivided into three units: lobate boulder deposits, boulder terraces, and boulder levees (Figures 2–5). The older debris-flow deposits are clast-supported, poorly to very poorly sorted, and composed of subrounded to subangular cobbles and boulders, pebbles and sands. Older debris-flow deposits have a smoother surface than more recent debris-flow deposits because post-depositional weathering of clasts produces fine sediment that accumulates between and partially buries clasts at the surface.

GEOMORPHIC EFFECTS OF DEBRIS FLOWS ON CHANNEL MORPHOLOGY

The volume of sediment eroded from the failure zones ranged from 2300 to 7500 m^3 (Table III). The volume of sediment eroded from the failure zones is variable, partially dependent on the size of the initial failure, underlying structure and lithology, intensity and duration of the precipitation that initiated failure, and the time elapsed since the last debris flow (Costa, 1984; Reneau and Dietrich, 1987; Benda, 1990). A comparison of the data in Table II with those in Table III indicates that structure and lithology appear to be the dominant influences on the volume of erosion in the failure zones. Debris flows that originate on dip or oblique-dip slopes of the orthoquartzite (Austin Run and Twin Run) are more likely to erode to bedrock, have thicker slide masses, and have greater erosional volumes than those originating on anti-dip or perpendicular-dip slopes underlain by interbedded shales and argillaceous sandstones (Kisamore Run and Gravel Lick Run).

For the three debris flows with transport/erosion zones, the volume of sediment eroded from the channels ranged from 4600 to 9800 m^3 and was 1·3 to 1·5 times greater than the volume of sediment eroded in the failure zones (Table III). Deposition was minimal in these zones and ranged from 500 to 1600 m^3 (Table III). Most of the sediment eroded by each debris flow was incorporated into their flow causing the debris flows to

progressively increase in size as they moved through the transport/erosion zone. In a sediment budget study of a small catchment in the Oregon Coast Range, Dietrich and Dunne (1978) estimated that 35 per cent of the total erosion by a debris flow was due to scouring of the channel bed during transport. Benda (1990), in a study of debris flows in the Oregon Coast Range, estimated that the total erosion of sediment from first- and second-order channels (equivalent to the transport/erosion zone in this study) by debris flows was, on average, double the volume of sediment that initially failed. This study, along with the studies by Dietrich and Dunne (1978) and Benda (1990), quantifies debris-flow erosion along steep, low-order channels.

The volume of sediment deposited in the deposition zones ranged from 2100 to 10 500 m^3 (Table III). Eighty-six to one-hundred per cent of the volume of sediment deposited by the debris flows occurs in this zone. Erosion by debris flow was minimal in this zone, approximately 300 m^3 (Table III). The volume of sediment deposited in the deposition zones was only 57 to 91 per cent of the total volume of sediment eroded in the failure and transport zones (Table III). Most of the sediment removed from the deposition zones was probably the result of erosion of the debris-flow deposits by floodwaters from joining tributaries immediately after deposition, as indicated by the presence of channels through the debris-flow deposits (Figures 2–5). The degree to which the deposits were reworked and incised by the floodwaters depends on the timing of debris-flow deposition with respect to the occurrence of the peak discharge of the tributary floodwaters. Although the timing of debris flows and peak discharge of headwater channels is poorly understood in the study area, the limited channel development and minimal erosion of debris-flow deposits on Gravel Lick Run (Table III) suggests that the debris flow occurred well after the peak discharge of the tributary floodwaters. In contrast, for the Austin Run, Kisamore Run and Twin Run debris flows, 30 to 40 per cent of the sediment delivered by the debris flows was eroded by floodwaters (Table III) and channel entrenchment into the debris-flow deposits is up to 3 m. This suggests that these debris flows occurred at approximately the same time as the peak discharge of the tributary floodwaters.

The volume of sediment eroded and deposited in the sediment-laden floodwater zones was quantified only in Austin Run and Gravel Lick Run. Approximately 3600 m^3 and 700 m^3 of sediment were eroded from the valley walls of Austin Run and Gravel Lick Run, respectively (Table III). Erosion was most extensive in narrow, steep reaches and exposed bedrock along the channel bottom (Figure 9). Most of the sediment eroded from the Austin Run sediment-laden floodwater zone was deposited on the surface of a pre-1949 debris fan or flushed into the South Branch Potomac River (Figure 2), whereas much of the sediment eroded in the Gravel Lick Run sediment-laden floodwater zone was deposited on the channel floor in this zone or transported further downstream (Figure 5). Reconnaissance of non-debris flow-impacted channels with similar drainage areas displayed only minor or no erosional and depositional features from flooding by the 1949 or 1985 storms. Channel erosion in the sediment-laden floodwater zones suggests that the erosive power of floodwaters in channels downstream from the deposition zones was enhanced by the influx of debris-flow-generated sediment.

The spatial distribution of sediment eroded and deposited during a debris flow is non-uniform with the most intense modification occurring in the failure and deposition zones (Figure 10). The debris flow maps and sediment distribution graphs show that erosion dominated the upper two-thirds of Austin Run, Kisamore Run and Twin Run (Figures 2, 3, 4 and 10). However, the total volume of sediment eroded in the transport/erosion zones of Austin Run, Kisamore Run and Twin Run is greater than the volume of sediment eroded in the failure zones (Table III). The variability in erosional volumes in the transport/erosion zones reflects changes in the relative erodibility of channel boundaries along the flow track as underlying lithology changes (Table III). Sediment distribution in the sediment-laden floodwater zones of Austin Run and Gravel Lick Run are characterized by a combination of erosion in narrow, steep reaches and deposition in wider, less steep reaches.

CONCLUSIONS

The geomorphic maps of the four large debris flows document the spatial variability of geomorphic processes and effects along the course of the flows. These detailed maps show a consistent spatial pattern of erosion and deposition along the flow tracks, with erosion being the dominant geomorphic process in the failure and transport/erosion zones and deposition dominating in lower-gradient channels. The presence of older debris-

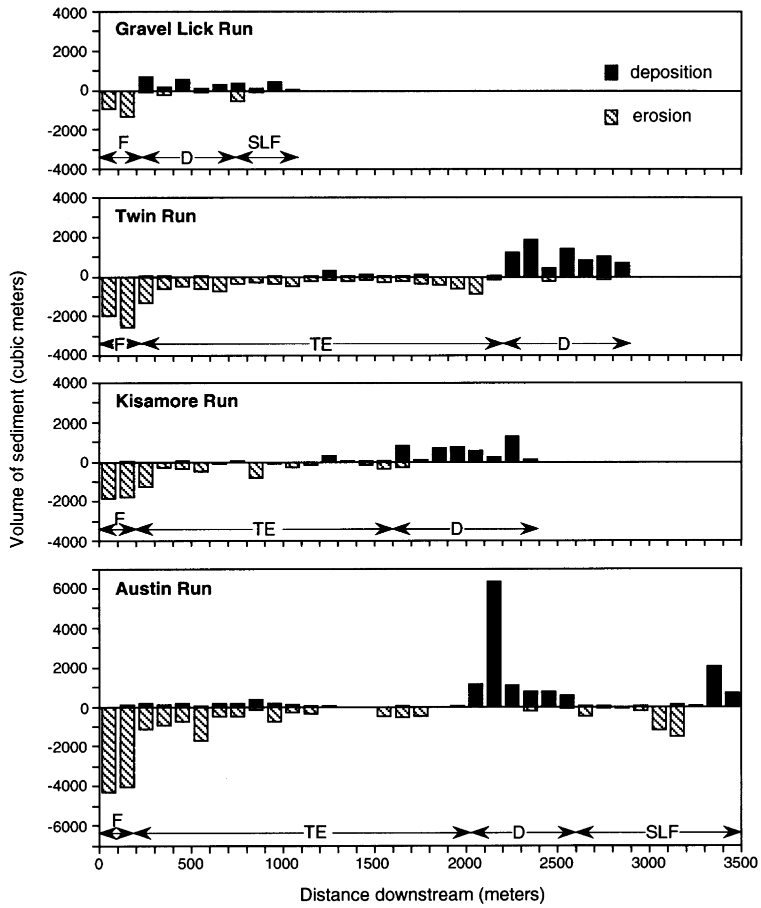


Figure 10. Histograms showing the distribution of eroded and deposited sediment on Austin Run, Kisamore Run, Twin Run and Gravel Lick Run. The failure (F), transport/erosion (TE), deposition (D) and sediment-laden floodwater (SLF) zones for each debris flow are delineated on their respective diagrams

flow deposits located adjacent to and downstream from the deposition zones indicates that debris flows are a recurring geomorphic process in low-order channels on North Fork Mountain.

The sediment budget constructed for each debris flow not only quantifies the amount of sediment eroded and deposited, but systematically shows how the sediment was distributed along the flow track. Although erosion was most intense in the failure zone, the total amount of erosion in the transport/erosion zone was greater than the total amount of erosion in the failure zone. This indicates that debris flows are effective erosive agents as they travel through channel systems. The sediment delivered to lower-gradient channels by debris flows was partially reworked and eroded by floodwaters from joining tributaries immediately after deposition. The extent of erosion by the floodwaters is dependent on whether the debris flow occurred in conjunction with the peak discharge of the floodwaters. Channels immediately downstream from the debris-flow termini experienced considerable erosion and deposition. In contrast, channels with similar morphology and drainage area, but lacking upstream debris flows, show little evidence of erosion and deposition from the 1949 and 1985 floods. This suggests that sediment delivered by debris flows into floodwaters immediately downstream by the debris termini will cause channel modification in these reaches.

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